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Your reference WAVELENGTH TUNABLE POWER METER

Patent application number 9903450.6
(The Patent Office will fill in this part)

Full name, address and postcode of the or of each applicant *(underline all surnames)*

OXFORD FIBER OPTIC TOOLS LTD
BARCLAYS VENTURE CENTRE
UNIVERSITY OF WARWICK SCIENCE PARK
SIR WILLIAM LYONS ROAD
COVENTRY CV4 7EZ

Patents ADP number *(if you know it)* 6760615002

If the applicant is a corporate body, give the country/state of its incorporation INCORPORATED IN ENGLAND

Title of the invention

WAVELENGTH TUNABLE POWER METER

Name of your agent *(if you have one)*

"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*

~~AS ABOVE~~ Swindell + Pearson
48 Friar Gate
DERBY
DE11 1GY

51/77 recd 13/3/00 Bm.

Patents ADP number *(if you know it)* 1578001.

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Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*
—		

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Number of earlier application	Date of filing *(day / month / year)*
—	

8. Is a statement of inventorship and of right to grant of a patent required in support of this request? *(Answer 'Yes' if:*
   a) any applicant named in part 3 is not an inventor, or
   b) there is an inventor who is not named as an applicant, or
   c) any named applicant is a corporate body.
   See note (d))

—

Patents Form 1/77

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Abstract	—
Drawing(s)	7

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Translations of priority documents	
Statement of inventorship and right to grant of a patent *(Patents Form 7/77)*	—
Request for preliminary examination and search *(Patents Form 9/77)*	
Request for substantive examination *(Patents Form 10/77)*	
Any other documents *(please specify)*	

11. I/We request the grant of a patent on the basis of this application.

Signature I J Murgatroyd Date 16 February 1999

12. Name and daytime telephone number of person to contact in the United Kingdom I. J. MURGATROYD 01203 323066.

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Oxford
Fiber Optic Tools Limited

WAVELENGTH TUNABLE POWER METER

Background to the Invention

Multi-channel optical communication systems are becoming widespread. These systems consist of 16 or more wavelengths of light travelling in a single-mode optical fiber. Each wavelength corresponds to a channel and information is encoded on to each channel. Each wavelength travels independently without interference with the other channels. When the 16-channel signal arrives at its destination, the individual channels (wavelengths of light) must be separated from each other so that the information carried on each channel can be decoded.

There is a requirement that the 16 different wavelengths should be monitored. Thus if one or more of the light sources (lasers) should fail or the wavelength of any source drifts, the system should be monitored and repaired as the failure occurs.

Current technology uses a bulk diffraction grating in an Optical Spectrum Analyser (OSA), whereby the light exiting from the optical fiber is focused on to the grating and the reflected light is focused back on to a detector. As the diffraction grating is rotated, the spectrum of the incoming light is measured.

This technology has several disadvantages. The diffraction grating is subject to mechanical shock and damage so the OSA is limited in its ruggedness and isolation from mechanical vibration. The bulk diffraction grating is limited in its accuracy and resolution by its mechanical movement. The grating is likely to drift with time and be affected by mechanical backlash, and so must be regularly calibrated. The light must be extracted from the optical fiber for measurement, requiring accurate focussing of the light on to the detector. All of these disadvantages lead to an expensive measuring instrument which is limited in its performance, is expensive and is not well suited for field monitoring of optical systems.

A fiber Bragg grating will reflect light within a narrow spread of wavelengths. If the fiber Bragg grating is stretched, the spacing of the Bragg grating will increase, so reflecting a longer wavelength. Conversely, if the grating is compressed, the spacing of the grating will decrease, so reflecting a shorter wavelength.

Summary of the Invention

We here reveal a wavelength tuneable power meter. The power meter can be used for such applications as to scan the spectrum of a multi-channel optical communication signal, detecting the presence, power and wavelength of all optical channels present, or for interrogating wavelength sensitive sensor arrays. We pass the optical signal into a fiber Bragg grating (FBG) which reflects

Fig 9 shows the detector output obtained over time for the architecture used in Fig. 8.

Fig 10 shows the provision of an internal reference wavelength to calibrate the FBG(s) as they are stretched.

2/7

only a narrow range of wavelengths of the light present in the optical signal. Any light in the input spectrum which corresponds to the reflection band of the FBG is reflected so that it passes into a detector. We scan the wavelength of the light reflected by the FBG into the detector by stretching the Bragg grating, so scanning the whole spectrum of signal.

A simple FBG must be strained by up to 1.8% in order to scan the spectrum from 1540-1560nm, and this is likely to break the fiber in far less than the 10,000 measurement cycles required. This invention uses two or more FBGs that each scan adjacent wavelength bands to reduce the maximum strain by nearly half, hence extending the power meter's lifetime. In addition, this invention reveals the use of two FBGs whose reflected wavelength is different by an (integer + fraction) times the optical channel spacing, establishing a Vernier scale where the FBG's measure the channels with their fixed spacing, thus reducing the maximum strain needed and extending the lifetime of the tunable power meter.

Brief Description of the Drawings:

Fig 1 shows the architecture of a FBG reflecting a narrow band of the incoming optical signal into a detector.

Fig 2 shows no light reflected into the detector when the reflection wavelength of the FBG lies between the channels of the incoming signal, but a reflection into the detector when the reflection wavelength of the FBG corresponds to one of the channels of the incoming signal.

Fig 3 shows a coated fiber held between two mandrels and cyclically stretched by moving the mandrels with respect to each other.

Fig 4 shows the number of cycles to failure, where the fiber is cycled between zero and a maximum strain, measured for three different maximum strains. The mean and 95% confidence limits are marked.

Fig 5 shows the architecture where the incoming signal is split so that it is reflected by two different FBGs, where the FBG have different but overlapping reflection bands, so reducing the maximum strain needed for the detection system to scan the whole spectrum.

Fig 6 shows the architecture where the incoming signal is passed into two in-line FBGs, where the two FBGs' reflection wavelengths are different by an (integer + ½) times the optical channel spacing.

Fig 7 shows the reflected wavelengths obtained from two FBGs arranged in-line for three different levels of strain.

Fig 8 shows the reflected wavelengths obtained from two FBGs arranged in-line where the two FBGs' reflection wavelengths are different by an (integer + 1/3) times the optical channel spacing.

Description of the Preferred Embodiments

Fig. 1 shows the architecture for a detection system in which the 16-channel optical signal is passed through an optical isolator X into a 50:50 2 x 2 coupler C. The output leg 2 of the coupler is passed into a Fiber Bragg Grating (FBG), G, which reflects back a narrow range of wavelengths into the coupler C and thence into the detector D which is attached to leg 3 of the coupler. The end of the Bragg grating and the output leg 4 of the coupler are terminated to prevent back-reflection, for instance by using an angled cleave. The detector D therefore detects a signal only if the input signal contains wavelengths corresponding to the reflection wavelength of the FBG.

Fig **2a** shows the FBG reflection band falling between two optical channels in the input signal, and so no light is reflected back into the detector D. Fig **2b** shows a case where the reflection band of the FBG corresponds to the wavelength one of the optical channels, hence the detector records a signal.

In this invention, the unstretched grating has a reflection band that is slightly shorter than any of the wavelengths in the optical signal, and so, in its unstrained state, it will not reflect light into the detector. However, as the grating is stretched, the reflection band progressively passes through each of the optical channels, in-turn reflecting each of the channels. Therefore, as the grating is stretched the optical spectrum is scanned.

Alternatively, the unstretched grating has a reflection band which is slightly longer than any of the wavelengths in the optical signal, and so, in its unstrained state, it will not reflect light into the detector. However, if the grating is compressed, the reflection band progressively passes through each of the optical channels, in-turn reflecting each of the channels. Therefore, as the grating is compressed, the optical spectrum is scanned.

Current technology has addressed the problem of compressing the Bragg grating. The grating is compressed so that it tunes across 30nm – 40nm of the spectrum – more than sufficient to measure a 16-channel system which typically occupies 1540nm – 1560nm. However, compressing a grating is difficult because the optical fiber is likely to buckle, so destroying the control of the compression of the grating. Typically, this has been solved by compressing the grating inside a cylinder of similar internal diameter as the optical fiber (for instance using a ceramic ferrule) so that the optical fiber is not able to buckle. However, it is inherently difficult to compress a fiber without buckling. Furthermore, repeated compression of a fiber inside a hard cylinder is likely to damage the fiber. In addition, friction between the fiber and the ferrule will lead to sticking and so non-linear compression of the fiber.

It would be easier to stretch rather than compress the optical fiber containing the Bragg grating, hence effecting a tuning of the reflection wavelength. Stretching will give linear extension of the fiber and no frictional damage to the fiber will occur in the absence of a hard ferrule. In the past, stretching the fiber has not been pursued because the fiber, being glass, is brittle and is likely to crack. This invention reveals methods of stretching fiber by the required amount to tune across the desired spectrum range of 1540nm – 1560nm without the grating failing due to cracking over several thousand cycles.

Tuning from 1540nm – 1560nm requires a change the reflected wavelength of 1.3%. The tunable power meter here revealed contains a Bragg grating which is stretched to alter the periodicity of the grating and so tune its reflected wavelength over the WDM spectrum. Taking into account

Poisson's ratio of 0.79, the fiber would have to be stretched by 1.64% to allow tuning across the entire spectral range. Allowing for extra stretch at the beginning and end of the tuning range, the glass fiber would have to be stretched by approximately 1.8% to tune across the entire spectrum. In a field application, the tunable power meter would be expected to survive for 10,000 cycles with a 90% reliability if it were used to check WDM spectra over a lifetime of 3 years. Therefore, the grating in the tunable power meter must by stretched by 1.8% 10,000 times in its lifetime.

Lifetime tests under a cyclical load were carried out on Corning single mode fiber (SMF). The number of cycles to failure was measured where the fiber was cycled between zero and a maximum stress. The coated fiber, 5, was held at two points so that it could be stretched by moving apart the holding points, as shown in Fig 3. The fiber was secured at both points by wrapping it several times around two mandrels, 6, 7, of approximate diameter of 25mm, with the coated fiber lying in a V-shaped screw thread, with the free end of the fiber glued onto the mandrel. One mandrel, 6, was fixed and the other mandrel, 7, was moved away with a controlled force, so stretching the fiber to a maximum strain. The mandrels were then moved back together again to give zero strain. The strain cycles was then repeated. The experiments were carried out at approximately 25°C and a relative humidity of 60%.

Fig 4 plots the number of cycles to failure against maximum load for 10 tests, 10 tests and 3 tests, corresponding to strains of 5%, 4% and 2%, respectively. The fiber is expected to fail due to stress-corrosion cracking. The graph shows that the fiber will last for at least 3,000 cycles when cyclically strained by up to a maximum of 2% with a 95% confidence limit. Extension of the curve shows that the fiber is likely to survive for at least 10,000 cycles when strained by 1.8% with a confidence limit of approximately 90% or more. In summary, Corning SMF can be stretched by 1.8% over 10,000 cycles, as required by a wavelength tunable power meter.

The above experiments were carried out with glass fiber that was coated with acrylate as it was drawn from the preform. This fiber would therefore be expected largely to be free from surface cracks which might lead to stress-corrosion cracking. However, in order to make Bragg gratings, the acrylate is stripped off and the glass is exposed to UV radiation, to form the grating, before being recoated. At every stage of this process, the glass is liable to suffer surface damage which will decrease its eventual lifetime when cyclically strained. Therefore, it is unlikely that a fiber into which had been written a Bragg grating, would be able to survive 10,000 cycles of 1.8% strain.

This invention reveals techniques by which the grating can be stretched by less than 1.8% and still tune across the entire spectrum.

The use of two FBGs that each scan adjacent wavelength bands would allow each fiber to be stretched by approximately half as much as compared to Fig 1, whilst still scanning the full wavelength range of 1540nm – 1560nm. Fig 5 shows the incoming light split by the 50:50 2x2 Coupler C. Each output from ports 2 and 4 of Coupler C is then passed through 50:50 2x2 Couplers E and F, respectively. The outputs from Couplers E and F are respectively passed into Gratings K and L. Grating K is stretched from 1540nm – 1551nm and the reflected signal is passed into Detector H, so scanning its reflection wavelength over channels 1 - 9. Grating L is stretched from 1550nm - 1560nm and the reflected signal is passed into Detector J, so scanning its reflection wavelength over channels 9 - 16. Consequently, the entire spectrum from 1540nm – 1560nm is scanned, but the maximum stretch on either of the gratings is less than 1.0%. This will dramatically increase the lifetime of the gratings. More than 2 overlapping gratings can be used, further reducing the maximum stretch required.

However, this instrument will have a Signal-to-Noise Ratio (SNR) worse by 3dB than the single grating architecture of Fig 1, because the signal is passed through an extra coupler. Furthermore, the cost will be higher because there are twice as many couplers, detectors and gratings. This invention also envisages splitting the signal into more than two gratings and detectors, so further reducing the maximum stretch required by each grating to allow the entire spectrum to be scanned

In summary, stretching two or more gratings reduces the total amount of stretch required, allowing the entire spectrum to be scanned whilst reducing the risk of the fiber breaking under repeated cycling.

Multiple gratings can be used to reduce the maximum amount of stretch and so increasing the lifetime can be achieved, whilst maintaining the S/N ratio, number of gratings, couplers and detectors the same as the single fiber case. This is achieved by using two gratings in the same length of stretched fiber. The gratings can either be written in different locations in the fiber, as shown in Fig 6, or are superimposed to reduce the length of fiber that needs to be stretched.

An example of the technology application would be 16 channels of a multi-channel transmission system. The centre wavelength of each grating would be separated by ~10nm, with the unstrained Grating M reflecting at 1540nm and the unstrained grating N reflecting at approximately 1550nm. The reflections of the two gratings are arranged to act as a Vernier scale with respect to the spacing of the channels in the optical spectrum. The reflection bands of the two gratings are different by (Integer + ½) times the optical channel spacing. Therefore, as shown in Fig 7, as the fiber is stretched, Grating M will reflect Channel 1 on the spectrum, as shown in trace 7a; further stretching will lose the Channel 1's reflection. As the fiber is progressively stretched, Grating N will reflect Channel 9, trace 7b, followed by Grating M reflecting Channel 2, trace 7c, and so on.

Consequently, the fiber need only be stretched by a maximum of 0.9% to cover the entire spectrum. This will significantly lengthen the lifetime of the TUNABLE power meter. This has the advantage over the architecture of Fig 5 because only one detector and one coupler are needed

Clearly, more than 2 gratings can be used to obtain a larger Vernier effect. For example, using 3 gratings, arranged on a Vernier scale, would require a maximum fiber stretch of approximately 0.7% to tune across the entire spectrum. However, the Vernier arrangement requires that the spacing of the optical channels should be fixed; if the spacing of the channels varies by too much, the results will be ambiguous. This limits the number of Vernier grating elements that can be used.

The use of two gratings in a Vernier scale, whereby the grating wavelengths differ by (Integer+1/3) of a channel spacing will reduce the ambiguity of the measurement; this is similar to using a 3 part Vernier scale, where the third element is missing. The power reflected can then be monitored to check that the sequence of power reflected from each grating is as expected from the two gratings which are present and the third "grating" which is absent.

Fig 8 shows the detector's output from two gratings written into the same optical fiber, with the same architecture as Fig 6, but where the reflection wavelengths of the two optical fibers differ by (Integer+1/3) of a channel spacing. Assuming that initially the gratings are unstrained, Trace 8a corresponds to Grating M reflecting Peak 1. As the fiber is stretched by approximately 0.033%, the reflection wavelength of neither grating corresponds to an optical channel, so the detector receives no reflection, as shown in trace 8b. Straining the fiber by a further 0.033%, Grating N

reflects Peak 9 of the input signal into the detector, as shown in trace 8c. Progressive further strains of 0.033% gives Grating M reflecting Channel 2, followed by no signal being recorded, etc, as shown in traces 8d and 8e, respectively. Fig 9 shows the detector output over time as the fiber is progressively stretched. Positions T indicate no reflected light where the reflection of neither FBG corresponds to any of the optical channels. Knowing that the gratings have reflection wavelengths which differ by (Integer + 1/3) channel spacings, the first channel detected after a zero peak must come from Grating N. In general, provided that the two grating's reflection wavelengths are different by (Integer + fraction) of a channel spacing, where the fraction is not ½, the grating from which a particular peak arises can be unambiguously determined.

Consequently, the use of two gratings with reflection wavelengths arranged on a Vernier scale against the channel spacing reduces the stretch required for a single fiber to tune across the entire spectrum. This will reduce the likelihood that the fiber will break whilst being stretched and so increases the lifetime of the tunable power meter.

This invention also envisages a combination of splitting the signal, into two or more gratings, as in Fig 5, and the use of Vernier grating elements. This will further reduce the maximum strain required or extend the range over which the grating can be measured, whilst reducing the likelihood of the fiber(s) breaking.

Furthermore, the use of gratings of different wavelengths allows the measurement of regions of spectrum in addition to the 1540-1560nm range. Thus the emerging spectral range of 1580nm – 1620nm can be measured, as can other spectral ranges which could be transmitted using optical fiber manufactured from Silica, Tellurite, Fluoride or other glass materials.

All of the above techniques reduce the power of the incoming signal due to the use of a 2 x 2 coupler, possible leading to poor Signal-to-Noise Ratios (SNR) in the detectors' output. The SNR can be improved by phase-locking the detector to small signal oscillations in the amount of stretching of the fiber. This can conveniently be provided by piezo oscillation of the fixed mandrel, 6, or moving mandrel, 7, of Fig 3.

The spectrum scanning systems here described are likely to be temperature sensitive and possibly be subject to drift over a period of time. This would lead to a loss of accuracy in determining the absolute wavelength of any optical channel, and in extreme circumstances might lead to confusion of one channel with its neighbour. This invention therefore envisages the incorporation of an internal wavelength reference.

Fig 10 shows a copy of Fig 1, except that the input 1 of coupler C is attached to a wavelength reference arising from an light emitting diode (LED) source and a reference Bragg grating R. The LED's light is passed through a Coupler P into the reference Bragg grating R whose reflection wavelength at standard temperature is known from independent calibration. The reflection from the grating R is then passed into Coupler C (via Coupler P) and thence into the stretchable grating G. Knowing the reflected wavelength of grating R allows grating G to be calibrated and hence calibrates the wavelength of the spectrum provided by stretching grating G. This provision of a calibrated wavelength can be used for a single grating architecture (Fig 1) or multiple gratings (Figs 5 and 6). The reference wavelength would normally not be used during a measurement of the incoming optical signal, and therefore the tunable power meter would be calibrated offline. Alternatively, if the reflection wavelength of grating R was set at a slightly shorter (or longer) wavelength than the shortest (longest) wavelength being measured, the tunable power meter could

be calibrated during each measurement.

All architectures in Figs 1-10 optionally include an optical isolator X to prevent any light reflected from any of the Bragg gratings being reflected back into the optical system that this tunable power meter is measuring.

Typical values for fiber Bragg gratings of Full-Width-Half-Maximum (FWHM) and Side-Lobe-Suppression-Ratio (SLSR) are 0.15nm and –25dB, respectively. A single diffraction grating stretched by 1.8% to cover the entire spectrum from 1540nm – 1560nm will estimate power in each peak to an accuracy of +/-5%. This figures arises because the side lobes are only suppressed to –25dB and the other 15 channels will contribute small amounts of power to the signal of the channel being measured, hence increasing the apparent detected power. The peak position will be determined to within the step size of the measuring system, which will be approximately 1/16th of the peak spacing, giving a wavelength accuracy of the peak position to approximately +/-0.05nm. Temperature effects will be negligible because of the internal calibration wavelength (see below).

Splitting the spectrum into two or more segments and stretching single diffraction gratings to cover that fraction of the spectrum will not add to the inaccuracy because it can be designed so that one peak is measured by at least two gratings.

The use of 2 or more Vernier grating elements will be more susceptible to variation in channel wavelengths and the resolution of the gratings because there will be significant overlap of the tails of the reflection wavelengths of each grating. If 2 Vernier elements are used, nearly but not exactly, ½ channel spacing apart, approximately 1% of the power in the tails of the two reflections will overlap (assuming 0.8nm channel spacing and FWHM of 0.15nm). This will slightly worsen the power sensitivity by approximately 1%. However, the Vernier grating elements may give ambiguous results if one channel drifts in wavelength.

The temperature sensitivity of the measuring systems here described will be substantially reduced if the Bragg grating providing the reference wavelength is mounted close to the Bragg gratings which are being stretched. Any temperature variation will therefore have a similar effect on all of the gratings, therefore temperature drift of the gratings being stretched is largely cancelled out by an approximately equal temperature drift of the calibration wavelength. The temperature accuracy can be further improved by calibrating the system performance with temperature and correcting for any errors.

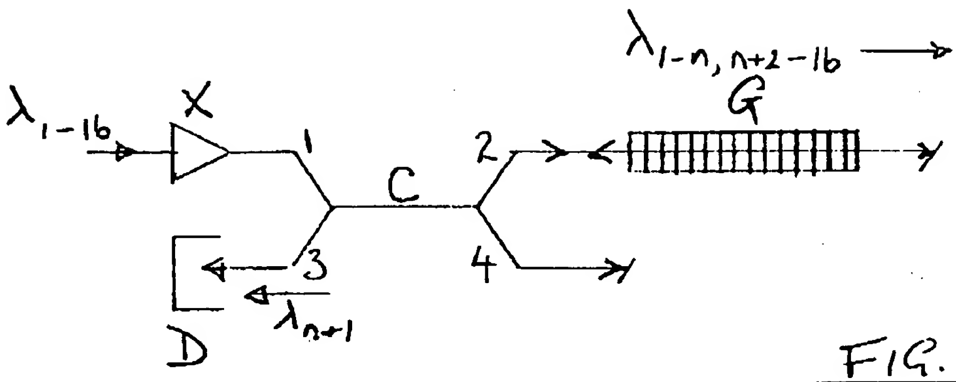

FIG. 1

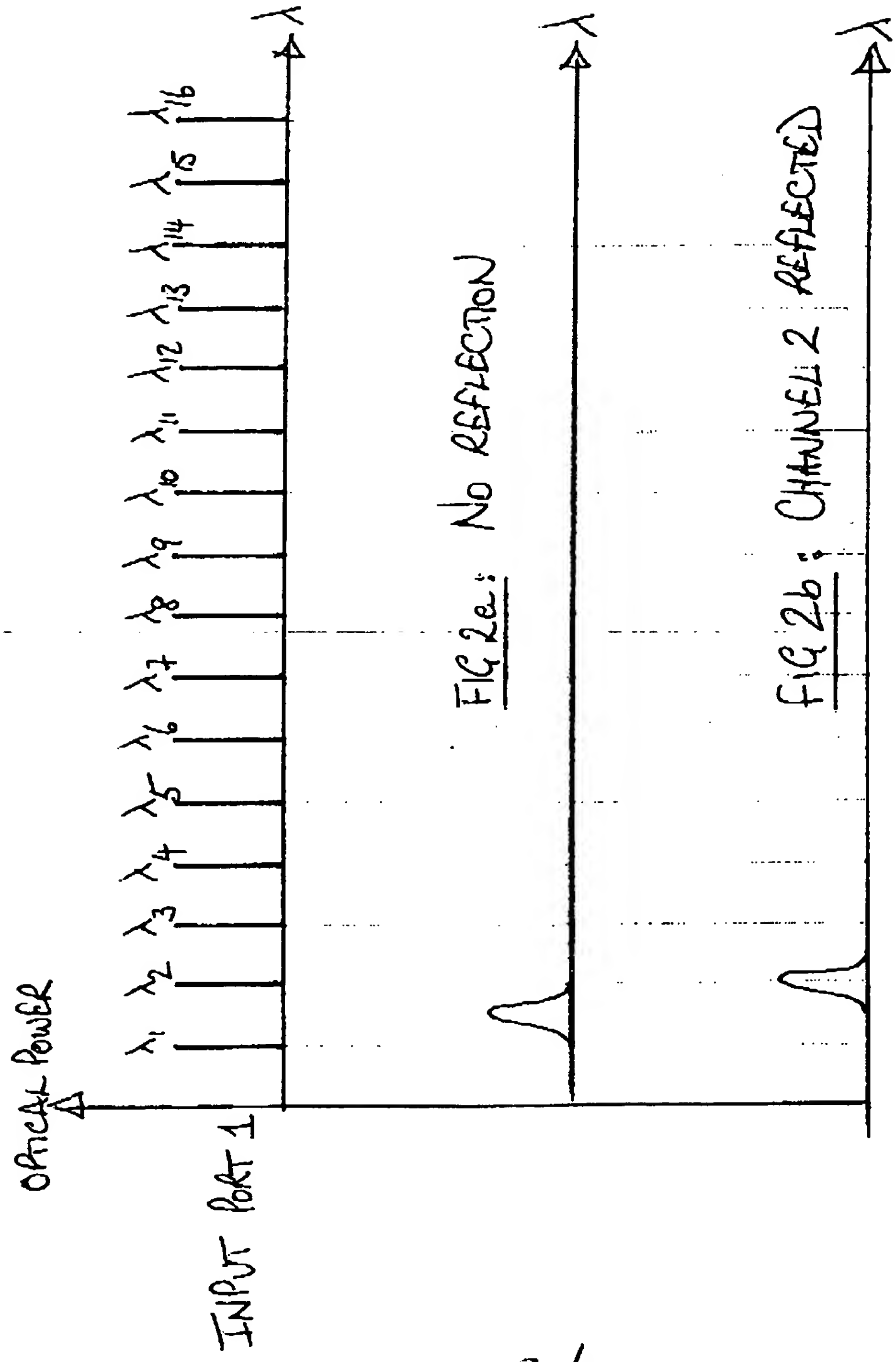
OPTICAL POWER
INPUT PORT 1
λ1 λ2 λ3 λ4 λ5 λ6 λ7 λ8 λ9 λ10 λ11 λ12 λ13 λ14 λ15 λ16
λ
FIG 2a: NO REFLECTION
λ
FIG 2b: CHANNEL 2 REFLECTED
λ

FIG. 2

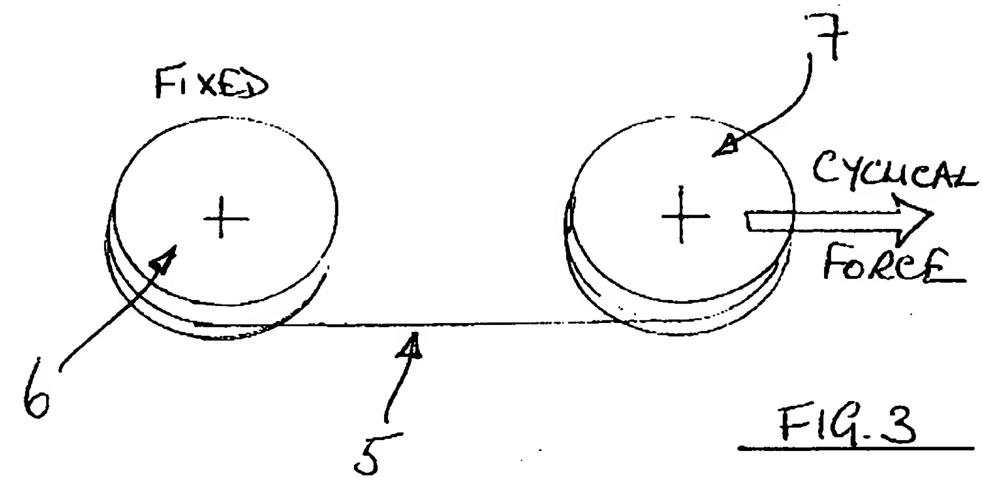
7
FIXED
CYCLICAL
FORCE
6
5

FIG.3

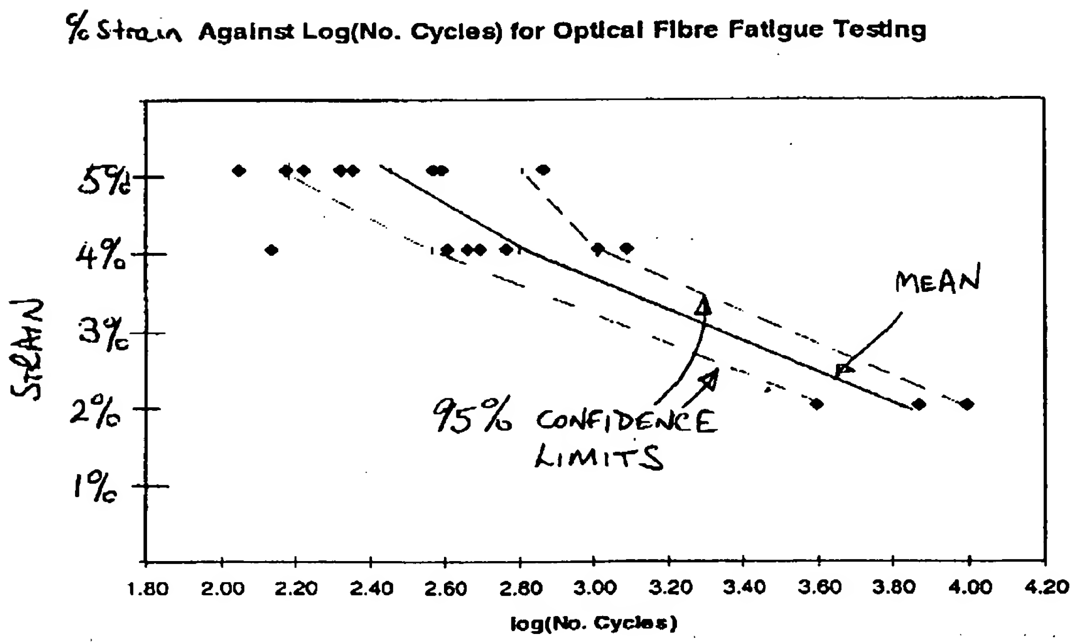
% Strain Against Log(No. Cycles) for Optical Fibre Fatigue Testing
5%
4%
3%
2%
1%
STRAIN
MEAN
95% CONFIDENCE LIMITS
1.80
2.00
2.20
2.40
2.60
2.80
3.00
3.20
3.40
3.60
3.80
4.00
4.20
log(No. Cycles)

FIG.4

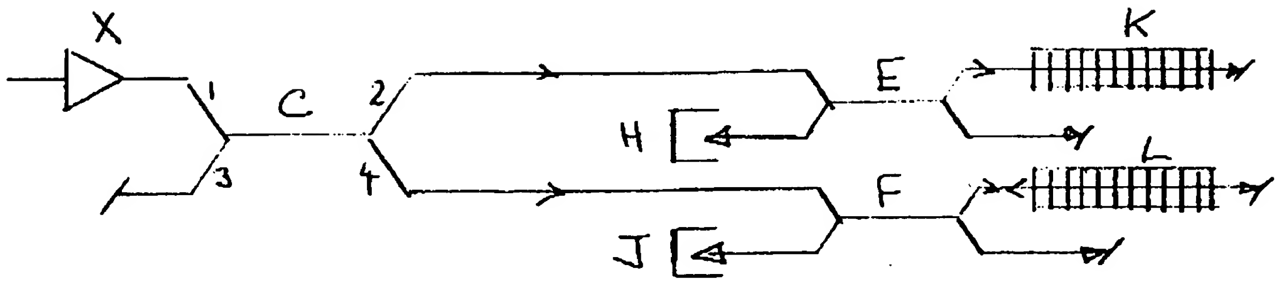

FIG. 5

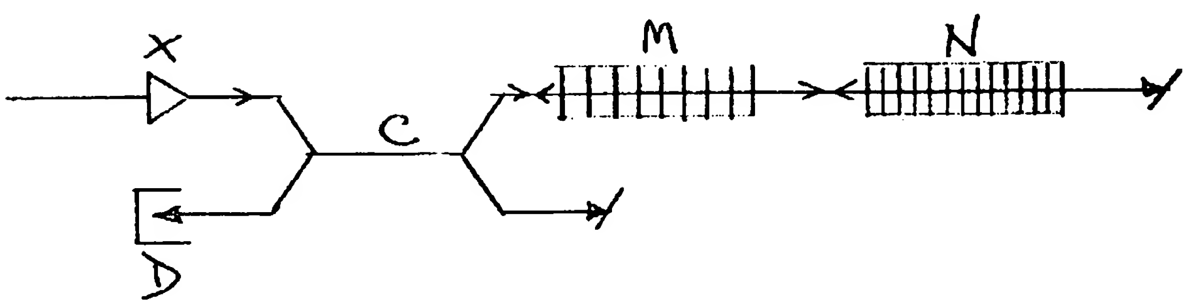

FIG. 6

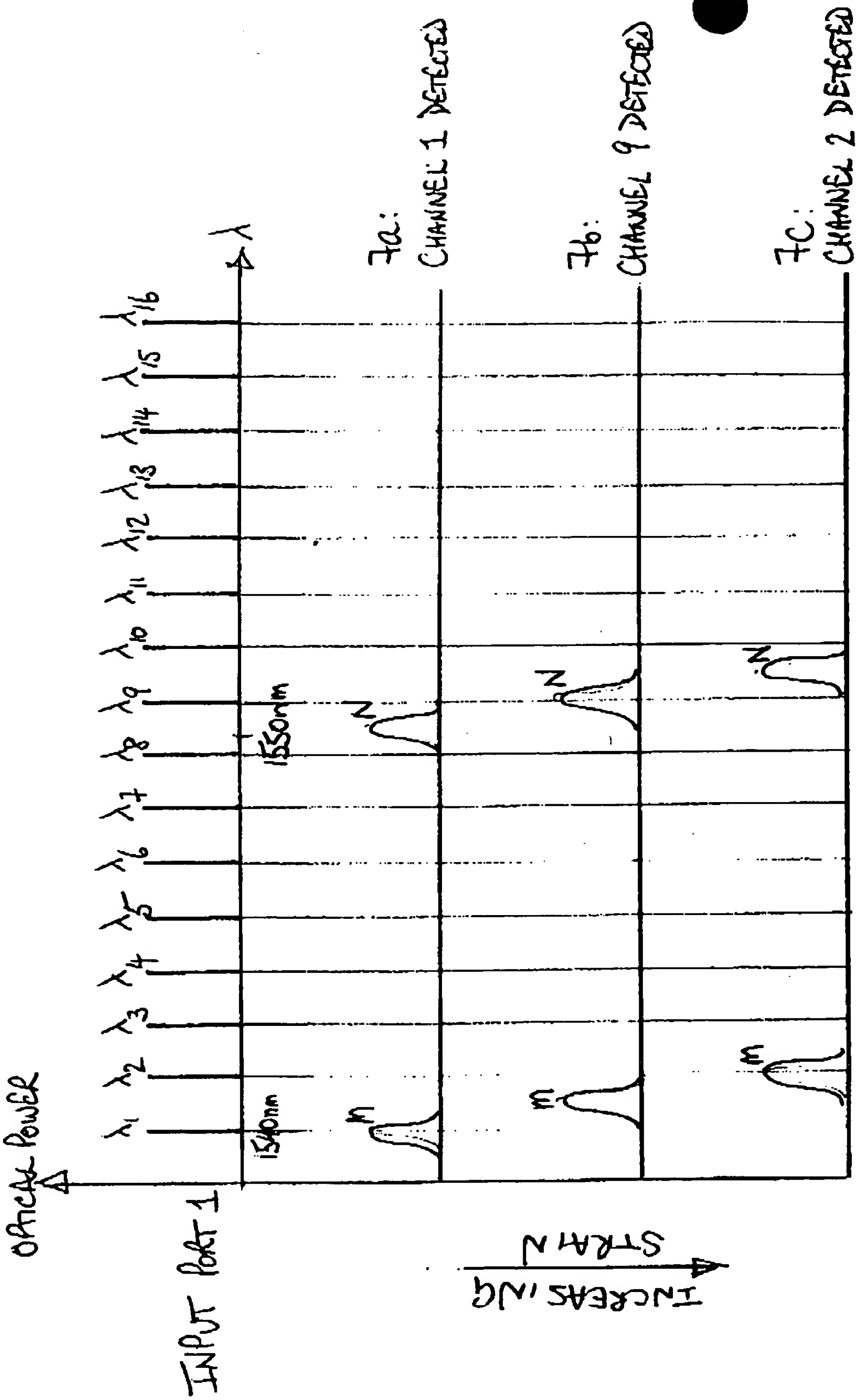
OPTICAL POWER
INPUT PORT 1
λ
λ1 λ2 λ3 λ4 λ5 λ6 λ7 λ8 λ9 λ10 λ11 λ12 λ13 λ14 λ15 λ16
1540nm
1550nm
7a: CHANNEL 1 DETECTED
7b: CHANNEL 9 DETECTED
7c: CHANNEL 2 DETECTED
m
n
INCREASING STRAIN

FIG. 7

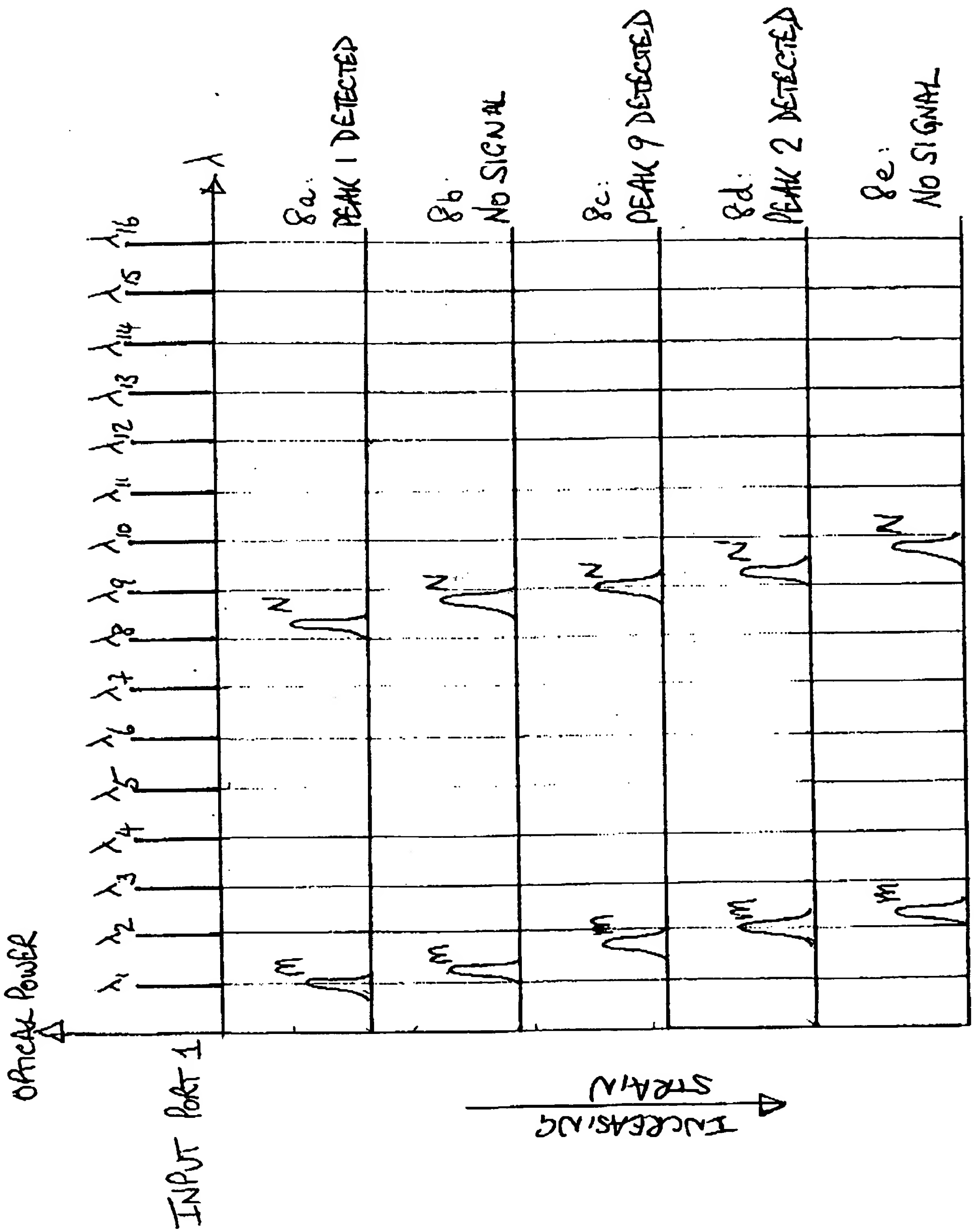
8a: PEAK 1 DETECTED
8b: NO SIGNAL
8c: PEAK 9 DETECTED
8d: PEAK 2 DETECTED
8e: NO SIGNAL
λ
λ_{16}
λ_{15}
λ_{14}
λ_{13}
λ_{12}
λ_{11}
λ_{10}
λ_{9}
λ_{8}
λ_{7}
λ_{6}
λ_{5}
λ_{4}
λ_{3}
λ_{2}
λ_{1}
OPTICAL POWER
INPUT PORT 1
INCREASING STRAIN

FIG. 8

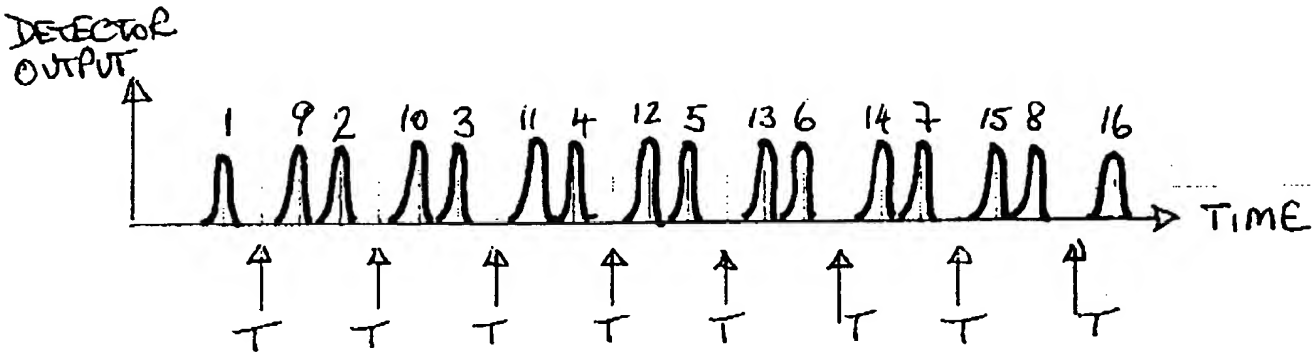
DETECTOR OUTPUT
1
9
2
10
3
11
4
12
5
13
6
14
7
15
8
16
TIME
T
T
T
T
T
T
T
T

FIG. 9

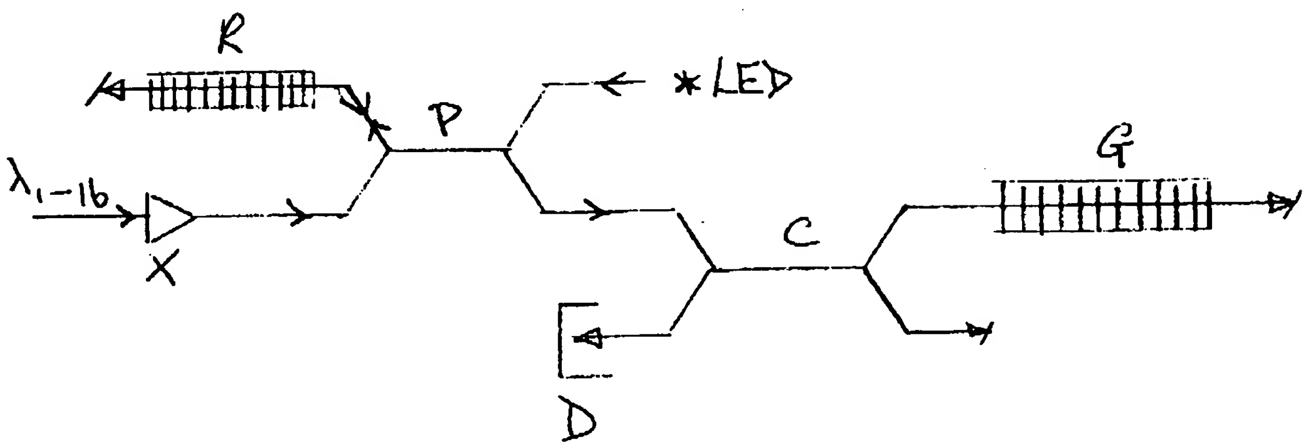
R
P
*LED
λ_{1-16}
X
C
G
D

FIG. 10

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13/03/00

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